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COMMITTEE ON THE PEACEFUL
USES OF OUTER SPACE

APPLICATIONS OF SPACE TECHNOLOGY FOR OCEAN RESOURCES DEVELOPMENT

Note by the Secretariat

1. The Working Group of the Whole to Evaluate the Implementation of the Recommendations of the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE 82), in the report on the work of its sixth session, proposed that a few more specific space applications studies should be carried out to demonstrate the potentials of space technology and identified a number of possible subjects for such studies, including the subject of ocean resources development (A/AC.105/513, annex II, para. 17).

2. The report of the Working Group was adopted by the Scientific and Technical Subcommittee in its report on the work of its twenty-ninth session (A/AC.105/513, para. 22), and the recommendations were endorsed by the Committee on the Peaceful Uses of Outer Space in its report on the work of its thirty-fifth session 1/ and by the General Assembly in its resolution 47/67 of 14 December 1992.

3. The present study has been prepared by the Secretariat in response to the request of the Working Group of the Whole. Its purpose is to review the applications of space technology for ocean resources development, and it is intended primarily for the benefit of countries that have not yet used space technology for this purpose but are interested in its potential benefits. The study was prepared using a variety of national and international sources, which are listed in the selected bibliography at the end of the study. During the preparation of the report, useful comments were received from the European Space Research Institute of the European Space Agency (ESA), the Federal Maritime and Hydrographic Agency of Germany, the Nansen Environmental and Remote Sensing Center of Norway and the Institute of Ocean Sciences of Canada.

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4. The following summary of the study appears in all the official languages of the United Nations. The full study, contained in the annex to the present document, is being distributed only in the language in which it was prepared (English) because of its technical character.

SUMMARY OF THE STUDY

5. Systematic scientific survey and study of the oceans began only some 200 years ago and was, until recently, largely limited to spot observations from ships. The advent of satellites, with their ability to survey the entire Earth on a repetitive basis, has radically changed the nature of oceanographic observations. From their vantage point in space, satellites are ideal platforms for global monitoring of dynamic phenomena and are now being extensively used for gathering data relating to the Earth's oceans, land surfaces and atmosphere.

6. Traditional oceanographic data involving direct measurements from individual ships or data buoys are very restricted in space and time. Studies of dynamic phenomena over large areas by such surface measurements are possible but extremely complex, time-consuming and expensive. Satellites, however, can easily collect data almost simultaneously over vast expanses of ocean and the adjacent land, providing continuous coverage in the form of images of the phenomena of interest, and can repeat those observations at regular intervals. Sensors on meteorological satellites, for example, provide coverage several times a day, thus permitting accurate modelling of rapidly changing processes, such as those in estuaries and in coastal areas, as well as more slowly changing ocean processes. The major limitation of satellite observations is that they are limited to surface or near-surface features, and oceanographic studies therefore often combine satellite observations with deep-water measurements or vertical profiles made from ships or buoys at selected locations.

7. The ocean features accessible to satellite observation include surface or near-surface colour, water temperature, wave height, surface roughness, large-scale surface topography and the presence and type of ice. Measurements of those features and their variation over space and time can be interpreted to provide information relating to biological productivity, fish location, currents, sea state, surface winds, water composition and quality, sedimentation patterns, pollution and other phenomena. Information on those phenomena can be used in turn to improve our understanding of ocean processes and their effects on the global climate, sustainable food production, weather and storm patterns and other long-term environmental factors.

8. The main instruments used for ocean observations from space are multispectral scanning systems that produce images of water colour or temperature and, more recently, imaging radar systems that provide information on sea state and which can make observations at night and through cloud cover. In addition to these imaging devices, other sensors such as microwave radiometers, scatterometers and altimeters provide linear traces of surface

temperature, wave height, wind speed and large-scale topography that can be accumulated over many orbits for compilation into low-resolution maps.

9. While large ground stations with major computer systems are required for receiving and processing most oceanographic data from satellites, the development of image and data analysis techniques using inexpensive microcomputers now makes it possible to do further analysis and interpretation at the local level. The lack of people trained in data analysis and interpretation, however, is a limiting factor in the use of satellite oceanographic data.

10. Remote-sensing satellites, such as the United States Landsat satellites since 1972 and the French Spot satellites since 1986, are routinely providing high-resolution images of the Earth's surface in a number of spectral bands, which, although designed for land applications, are also useful for studies of coastal areas and oceans. Operational meteorological satellites, designed for observations of the atmosphere, also provide some useful observations, particularly relating to large-scale rapidly changing phenomena.

11. A number of experimental satellites have been launched with sensors designed specifically for ocean observations. The United States of America has launched Geos 3 (1975), which first demonstrated global altimetry for ocean circulation as well as wind and wave studies, Seasat (1978), which carried the first imaging radar for wave and ice studies as well as a scatterometer for wind speed and direction and an improved altimeter, the Coastal Zone Colour Scanner (CZCS) (1978), designed for detailed studies of ocean colour, and Geosat (1985) with a radar altimeter used for the study of wave heights and ocean topography. The Union of Soviet Socialist Republics launched its first experimental oceanographic satellite Cosmos-1500 in 1983 for sea-state and ice mapping and subsequently launched a number of similar satellites in the Cosmos and Okean series. The Japanese Marine Observation Satellites (MOS) (1987 and 1990) carry multispectral scanners designed for coastal and ocean studies.

12. The 1990s have already witnessed a major increase in the availability of satellite ocean observations, and in particular of radar data. The recent launchings of the European Remote Sensing satellite (ERS-1), the Japanese Earth Resources Satellite (JERS) and the United States/French Topex/Poseidon satellites, together with other ocean observation satellites planned for the near future, are expected to dramatically expand the operational applications of satellite data for maritime activities. The vast amount of data now becoming available, and the rapid advances in computer technology to extract information from those data, are greatly increasing the potential benefits that can be realized through space technology.

13. Satellite observations are generating economic benefits for fisheries, for shipping operations, for offshore oil and gas development, oil spill monitoring and disaster warning. For fisheries, research has shown that a number of valuable species of fish tend to concentrate in waters of a certain temperature, along temperature boundaries or in areas of cold-water

upwelling. Satellite radar systems provide information on sea state and on ice distribution which can be used to substantially reduce travel time for ships and improve safety for offshore operations. Satellite observations can also, under certain conditions, map the distribution and evolution of oil spills and other pollution.

14. Applications of satellite data to fisheries began in 1971 as an experiment to assist purse-seine tuna fishermen in California. Today, satellite-derived information indicating the location of fish is provided to fishermen by agencies in France, Japan, New Zealand, the Russian Federation, the United States and other countries. Meteorological satellites provide daily thermal infrared observations that are used to identify major upwelling areas where fish tend to concentrate.

15. In the northern and southern areas of the world's oceans, ice poses a major obstacle and threat to shipping and offshore oil and gas operations. The all-weather capability of satellite radar systems provides a reliable means for operational monitoring of ice location and movement. The unique ability of radar systems to distinguish between very hard multi-year ice and weaker first-year ice is of major importance to both ice-breakers and general shipping. In addition, ship movements can be monitored by means of their tracks in the ice.

16. In addition to the immediate benefits, studying the oceans contributes to the understanding of the processes that govern weather patterns and climate change and affect long-term agricultural productivity and other aspects of human habitats. The oceans have an enormous capacity for storing heat, and the exchange of energy between the oceans and the atmosphere has a major influence on weather. Ocean currents, driven by wind and the sun, transport heat from the tropics to the polar regions and mix warm surface water with deep cold water. Satellite observations are used to map the dynamics of those currents and have revealed variations in the height of the sea surface of about 1.5 metres associated with the currents. Satellite observations of sea-surface temperature patterns such as those associated with the El Niño phenomenon in the Pacific, combined with meteorological observations, have revealed previously unsuspected correlations between weather patterns continents apart.

17. For most of the ocean, away from the influence of runoff from land, variations in colour are due primarily to phytoplankton, the microscopic, freely drifting organisms that form the base of the marine food chain. In addition to sustaining fisheries and other marine life, phytoplankton plays an important geochemical role in the global carbon cycle by absorbing atmospheric carbon in the upper layers of the ocean. Part of the resulting organic carbon eventually sinks to the seabed and is removed from circulation, thus reducing atmospheric carbon dioxide and global warming due to the greenhouse effect.

18. An accurate knowledge of ice-sheet surface topography is an essential requirement for determining ice-sheet dynamics, mass/balance variations and the effect of ice sheets on weather and climate. Until recently, knowledge of

ice-sheet topography was very limited owing to the vast surface areas involved and the logistical difficulties and high costs of polar fieldwork. Satellite altimetry is providing a means for systematic and repetitive mapping of the polar ice sheets, contributing to studies of their effects on and response to global warming and other climate changes.

19. While shipping, offshore oil and gas development, fisheries and coastal-zone development offer great economic benefits, they also pose risks to the marine environment and its sustained productivity. To assist in the protection of the marine environment, satellites provide weather and ocean current information as well as overviews of water colour and sea-surface temperature anomalies, which may be associated with water pollution phenomena. Satellite observations are also useful for identifying oil spills that occur outside the normal range of coastal patrol aircraft and for monitoring long-term effects of spills.

20. In addition to these new capabilities for oceanographic and marine resource surveys, satellites are being used for global maritime communications, navigation, search and rescue, and marine weather forecasting. Maritime communication satellites, for example, are used for transmission to ships at sea of information on fisheries, sea state, ice movements or storms. Information from oceanographic satellites on sea-surface temperature and wind speed can be used in conjunction with meteorological satellite data for marine weather forecasting.

21. While communications, meteorological and land remote-sensing satellites have long been operational, oceanographic satellites and their applications have been largely experimental. The users of satellite oceanographic observations have not been able to rely on a continuing supply of consistent data, which has hindered the development of operational applications and limited the economic benefits. The new satellites launched recently and the satellites planned for the next few years offer hopes that data will become more readily available and will be more widely used for the benefit of all countries.

Notes

1/ Official Records of the General Assembly, Forty-seventh Session, Supplement No. 20 (A/47/20), para. 29.

Annex

APPLICATIONS OF SPACE TECHNOLOGY FOR OCEAN RESOURCES DEVELOPMENT

Study by the Secretariat

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INTRODUCTION

1. The study of the ocean and marine environment is essential from both the economic and scientific viewpoints. Covering more than two-thirds of the Earth's surface, the oceans are major sources of food and raw materials, provide inexpensive global transportation, and play a large role in determining weather and climate. The study of marine biological productivity, the dynamics of ocean currents and waves, heat storage and transport, wind patterns over the oceans, ocean topography and interactions at the ocean-land and ocean-atmosphere interfaces are indispensable to a better understanding of the global environment and long-term climate trends. The importance of understanding interactions between the oceans and climate has recently been increased by concerns over global warming due to the build-up of carbon dioxide in the atmosphere, which may result in long-term changes in sea level and in the polar ice caps. In addition, pollution and contamination of the seas from industrial and municipal wastes and oil spills, with their deleterious effects on marine life, make it urgent to study the total land-ocean-atmosphere system as an integrated whole in order to protect the long-term productivity and habitability of our planet.

2. Such concerns have led to the initiation of several international programmes for observing and studying atmospheric, oceanic, land-surface and environmental processes on a global scale. Examples are the World Weather Watch (WWW) and the World Climate Programme (WCP) coordinated by the World Meteorological Organization (WMO) and the World Climate Research Programme (WCRP) organized by WMO and the International Council of Scientific Unions (ICSU). International research programmes specific to oceanography include, as part of WCRP, the World Ocean Circulation Experiment (WOCE) and the Tropical Oceans and Global Atmosphere (TOGA) programme aimed at modelling oceanographic and atmospheric processes. Other ambitious programmes include the Global Energy and Weather Cycle Experiment (GEWEX) and the International Geosphere-Biosphere Programme (IGBP), which will be implemented in the 1990s and may continue well into the 21st century. In-depth study of the oceans and the marine and coastal environment are an integral component of these programmes, which will collect, process and analyze a wealth of data from a variety of sources. Space information systems, because of their global reach, will play a vital role in the acquisition, recording, processing, transmission, exchange and analysis of these data.

3. From the economic standpoint as well, the oceans are of crucial importance. They are vast reservoirs of both living and non-living resources, some of which are undeveloped or underdeveloped. Marine life is a valuable source of food for the world's under-nourished or hungry habitants, while continental shelves, continental margins and the ocean bed contain a wealth of hydrocarbon and mineral resources. The increasing demand for food, minerals and energy in the world could be met, at least partially, from resources in and under the oceans and seas. Development of these resources, however, must be based on thorough and detailed study of the marine environment. Space-based data collection and information systems can play an effective role in providing the needed information.

4. In addition to these new capabilities for oceanographic and marine resource surveys, satellites are being used for global maritime communications, navigation, search and rescue, maritime weather forecasting and storm and disaster early warning systems, all of which play a part in development of ocean resources. The present study, however, concentrates on observations from space of marine resources and oceanographic conditions, by means of remote sensing, oceanographic and meteorological satellites.

I. REMOTE SENSING OF THE OCEANS

A. Background

5. Systematic scientific observation and study of the oceans began only some 200 years ago, and until recently oceanographic surveys were made mostly from ships, which are very limited in their area of observation and opportunities for repetitive and systematic coverage. Aircraft have also been used for marine surveys, particularly in coastal areas, but for the systematic and repetitive observations over vast areas that are required for comprehensive studies of the oceans, both ship and aircraft surveys are prohibitively expensive or simply unfeasible. From their vantage point in space, satellites are ideal platforms for global repetitive monitoring and are essential for monitoring large-scale dynamic processes. Meteorological satellites, for example, provide coverage several times a day, thus permitting study of rapidly changing processes such as estuarine and coastal currents.

6. It should be noted, however, that satellite observations are largely limited to surface or near-surface layers of the ocean and cannot provide information on deeper phenomena or processes. Ocean features accessible to observation from space with current technology include water colour, surface temperature, wave conditions and sea level. A combination of vertical profiles from ships or buoys, local detailed surveys by aircraft, long-term coastal observations and large-scale repetitive surveys by satellites is generally needed to provide data for a full understanding of ocean conditions and processes.

7. To convert observational data into useful information for ocean resource development or environmental planning, satellite data must be combined with data from aircraft and surface sources and interpreted in light of theoretical knowledge to generate a model of the physical, chemical, biological and geological character of the ocean. Taking into account economic factors and legal and policy considerations, knowledge of the ocean can then be interpreted and used as a basis for economic and environmental decision-making.

8. The main sensors that have been used for satellite observations are multispectral scanners operating in the visible and infrared parts of the electromagnetic spectrum. More recently, imaging radar systems, which operate in the microwave region of the spectrum and can be used day and night and through cloud cover, have come into use and are expected to provide more and better oceanographic data in the future. In addition to those sensors, which produce images for both land and water studies, there are a number of other lower-resolution, non-imaging sensors that operate in the microwave spectrum and are used especially for oceanography, including microwave radiometers for precise temperature measurements, scatterometers for observing sea-surface conditions and wind speed, and altimeters for studying ocean topography.

9. The major international sources of satellite remote sensing data have been the United States Landsat satellites, operating since 1972, and the French Spot satellites, operating since 1986. Those satellites, however, carry multispectral scanners that were designed primarily for land observations. The Coastal Zone Colour Scanner on Nimbus 7, designed specifically for water studies, had more spectral bands in the blue and green spectrum where water penetration is greatest, and greater sensitivity to the subtle differences in brightness that characterize water bodies. However, only one CZCS was launched and it is no longer operating.

B. Microwave remote sensing

10. The development of satellite imaging radar systems and other microwave sensors marked a major advance for oceanographic observations. However, due to the small number of spacecraft that have been equipped with such sensors and the complexity of data handling, radar coverage has been very limited both geographically and historically. Beginning with the launch of the European Remote Sensing ERS-1 satellite in 1991 and the Japanese Earth Resources Satellite JERS-1 in 1992, satellite radar data is now available on a more regular basis.

11. The Seasat satellite, which was launched by the United States in 1978 and operated for 3 months, demonstrated that a satellite radar could produce images of ocean waves from space, although it also showed that radar images are more difficult to interpret than multispectral scanner images. One of the difficulties is that satellite radar systems use the doppler shift of the radar echoes to determine the position of ground elements, and hence moving objects will be shifted away from their real position. For instance, when a radar produces an image of a moving ship and its non-moving wake, the ship does not appear at the head of the wake, but to one side of it. Knowing how radar operates, the interpreter can allow for this effect, and even take advantage of it to estimate the speed of the ship. For waves, however, the distortion is more difficult to contend with.

12. In addition to observing waves and ships, radar can sometimes detect oil slicks as an area of relatively smooth water caused by the wave damping effect of the oil. Radar can also provide information on the bottom surface in shallow coastal waters through the influence of the bottom on surface roughness patterns. According to some investigators, radar can also distinguish ocean fronts where bodies of warm and cold water meet, analogous to weather fronts in meteorology. Knowing the location of ocean fronts is particularly useful for fishing fleets looking for concentrations of fish.

13. Due to the difficulties of recording and storing the vast amount of data produced by satellite radar systems, about 100 megabits per second, radar data can generally be collected only when the satellite is in direct contact with a ground station equipped to receive its signals. Hence, a polar-orbiting radar satellite like ERS-1 requires a large number of ground receiving stations distributed all around the world to provide global coverage. In addition, the signal emitted by the radar demands so much power that the full capabilities of the system can only be used for about 10 minutes in each 100 minute orbit. In the non-imaging "wave mode," the radar reflections from an area of about 5 square kilometers every 200 or 300 kilometers along the satellite track are analyzed on board the satellite to provide information on the dominant wavelength and direction of ocean waves. Those non-image data can be recorded on-board and transmitted to a ground station once every orbit. Taken together, they allow scientists to derive a rough measure of the state of the oceans.

14. A radar altimeter uses a dish antenna pointing directly downwards to send out pulses of microwaves and detect the reflected signals, using the time delay as a measure of the distance from the satellite to the surface. A precise knowledge of the satellite orbit allows conversion of that distance into ocean topography relative to mean sea level or any other reference level, to an accuracy of a few centimetres. Furthermore, the shape and intensity of the radar echo compared with the transmitted signal provides information on the height of waves and on wind speed. As the reflection from the peaks of the waves will return to the satellite sooner than those from the troughs, the spread in time of the return signal is a measure of the range of wave

heights below. When the surface is roughened by wind, more of the transmitted pulse will be randomly scattered and less will be reflected back to the satellite, hence the weaker the return pulse, the higher the wind speed at the surface. These measurements on the return pulse are usually carried out about one thousand times a second and processed on board to give an average value roughly twenty times per second.

C. Physical oceanography

15. Multispectral scanners operating in the visible and near-infrared spectrum provide information on water colour, which can be interpreted in terms of turbidity, water composition and the presence of phytoplankton or other marine vegetation. In general, these parameters do not vary continuously, but are more or less homogeneous within water masses, which often have sharp boundaries separating them from other water masses. Multispectral images can therefore be used to study the mixing of different bodies of water, such as ocean currents or rivers entering the ocean. Blue and green wavelengths penetrate the water to the greatest depth and provide information on turbidity. Near-infrared wavelengths do not penetrate the water, but reveal surface vegetation, which reflects strongly in the infrared. Yellow and red wavelengths have intermediate penetration and can be used in conjunction with other bands to distinguish surface from subsurface phenomena. Observations of the intensity and distribution of turbidity, particularly if calibrated from surface measurements, provide information on sedimentation patterns relating to coastal erosion and ship channel maintenance. In shallow and clear water, it may be possible, using blue or green wavelengths, to observe light reflected from the bottom and deduce information relating to the depth and nature of the bottom.

16. While detailed study of open water phenomena are best done with sensors designed for oceanographic observations, coastal studies can often be done with remote sensing satellites designed for land applications. Where aquatic vegetation is not too dense, images in near-infrared bands generally show a strong contrast between dark water and lighter land, allowing accurate coastline mapping. Comparison of images acquired at different times can reveal changes in the coastline due to erosion or deposition. Where there is aquatic vegetation, repetitive coverage at near-infrared wavelengths shows the seasonal or long-term changes in vegetation distribution and vigour.

17. Multispectral scanners can also produce images based on thermal infrared radiation that is given off by surface features depending on their temperature. Thus thermal data will show warm objects or surfaces as bright and cold objects as dark, although it is also possible to process the data to produce negative images, for example in meteorological images in which cold clouds appear white and the warm land appears dark. Images processed for oceanographic applications generally show warm water as light and colder water as dark. As with water colour, a major application of thermal mapping of water is to distinguish between water masses and to show how they mix. Meteorological satellite thermal images of the east coast of North America, for example, clearly shows the warm Gulf Stream, with eddies of warm water 100 km in size spinning off into the colder water on either side, diffusing heat as they do so.

18. Ocean current patterns can be seen from space not only as colour or temperature differences, but also as differences in sea level. For example, there is a height difference of 1.5 meters across the Gulf Stream, with the eddies appearing as depressions in the sea surface. Such differences in sea level due to major currents are easily seen on maps of sea level compiled from satellite radar altimeter traces.

19. One of the most important and surprising results from the Seasat radar altimeter was a topographic map of the deep seabed as revealed by differences in surface level. Seasat altimeter data showed variations in surface level of as much as 100 meters corresponding to mountains, trenches, ridges and faults on and below the deep seabed at depths of several kilometres. Those features affect the Earth's gravitational field and thereby influence sea level. While it is difficult to separate the differences in sea level due to gravitational forces from those due to currents, it is not impossible. Changes caused by gravitation do not move and so any change in topography over time can be attributed to currents, winds or tides. Information on the Earth's gravitational field can also be determined from precise tracking of orbiting satellites, and the differences between the observed sea level and the gravitationally expected sea level would indicate differences due to currents.

20. Early data from ERS-1 has reinforced expectations of the value of satellite radar and other microwave observations of ocean features such as currents, waves, wind patterns, temperatures and eddies, particularly under moderate wind conditions (4 to 10 m/s). Much more experimentation will be required, however, before the full range of applications of the data is understood.

D. Marine weather and climate

21. Meteorologists already know much about processes within the atmosphere that lead to long-term climate change, but further study of the effects of the oceans is still needed. The oceans have an enormous capacity for absorbing heat from warmer air and releasing heat to colder air, thus making a major contribution to global heat exchange and determining regional climate patterns. As warm water flows from the tropical Atlantic towards the Arctic Ocean in the Gulf Stream, for example, about 10^{15} watts of heat is released into the atmosphere, equivalent to the output of a million average power stations. This heat warms the eastbound winds across the Atlantic, making Western European winters much milder than those in eastern North America. The oceans provide more heat to the atmosphere than the Sun does directly, and the top 3 meters of the ocean contain as much heat as the entire 100 km thick atmosphere.

22. Circulation currents transport heat not only horizontally, but also vertically, mixing warm tropical surface water down to depths of hundreds or even thousands of meters. Vertical transport also occurs when cold polar water sinks, creating deep cold currents from the poles towards the equator. But while the land and the air can change temperature in a matter of hours and transfer energy around the globe in a few days, the deep, slow-moving ocean currents can take centuries to transfer heat from one side of the world to the other.

23. Oceanographers know something about these processes from observations by ships and aircraft, but there is no substitute for the vast amount of data that satellites can produce every day. Since the launch of the ERS-1 satellite in 1991, wind and wave information derived from its radar data are progressively being incorporated into weather and climate models.

24. Satellites are particularly important for providing data about the Southern Ocean, the only unbroken ring of water that links the Atlantic, Pacific and Indian oceans, where few ships go. Satellites in polar orbit will also allow scientists to monitor the development of polar sea ice and the thawing and freezing cycles of the polar caps.

25. Changes in ocean circulation patterns and sea-surface topography are important factors in climatic changes. The global ocean deep circulation is determined primarily by descending currents of cold water off Greenland and Antarctica. Radar altimeter data such as that of ERS-1, integrated with other information on global oceanic heat transport, will play an essential role in global change monitoring.

26. A particularly interesting example of periodic climate change that has been studied by satellite is the El Niño phenomenon in the Pacific with its recurrent changes in ocean currents and weather patterns. The El Niño occurs at irregular intervals of several years and lasts for about six months, causing widespread changes in rainfall patterns including drought in Australia, rainstorms in Chile, disappearing shoals of fish and crop failures. Satellites have proved essential for studying and predicting those changes, through thermal infrared measurements of sea-surface temperature and current patterns, weather satellite observations of rainfall patterns, and remote sensing satellite observations of changed agricultural conditions.

E. Biological productivity

27. Over most of the oceans, away from the influence of runoff from land, variations in colour are primarily due to the varying concentration of phytoplankton, the microscopic, freely-drifting organisms that form the base of the marine food chain. Open oceans with very sparse life are deep blue, the colour of pure sea water, while the waters of more productive coastal regions are coloured green by chlorophyll and other plant pigments in phytoplankton. The pigments absorb blue and red light and reflect in the green region of the spectrum. The colour of the sea is therefore directly related to its biological productivity.

28. Oceanic phytoplankton, using the energy from sunlight for photosynthesis, produces the organic matter that sustains other marine organisms ranging from microscopic animals to the largest whales. In the process, inorganic carbon dissolved in sea water is transformed into organic carbon. Because of its central importance to marine biological processes, the rate at which photosynthesis proceeds is called primary productivity.

29. In addition to sustaining marine life, phytoplankton plays an important role in the global carbon cycle by taking up carbon from the surface waters of the ocean. The carbon removed from the surface waters is replenished by carbon dioxide from the atmosphere, while a proportion of the organic carbon produced by phytoplankton eventually sinks to the seabed, thus removing carbon from circulation. A substantial portion of the atmospheric carbon dioxide generated by human activities, from burning fossil fuel for example, is thus absorbed by the oceans, thus limiting the greenhouse effect and global warming.

30. Oceanographers have developed a range of techniques to measure primary productivity, but most require direct measurements from ships, which often can perform only one analysis per day. While these methods are indispensable for determining how factors such as sunlight and the concentration of nutrients influence photosynthesis, they are inadequate for monitoring primary production over large areas of the ocean or over long periods. To understand the role of the ocean in the global carbon cycle, it is necessary to know how productivity varies geographically and over time. Since the life cycle of phytoplankton is about 2 to 5 days, the only way to study the dynamics of primary productivity over large areas is by satellite.

31. Estimating phytoplankton through observation of ocean colour from orbit, however, is not a simple process. A multispectral scanner in space receives more sunlight scattered by particles and molecules in the atmosphere than light reflected from the ocean surface. The atmospheric effects must therefore be corrected for in order to extract information on ocean colour. The ocean colour information must then be analyzed to distinguish the light reflected by plant pigments from the light reflected by other molecules in the water. One procedure is to calibrate the satellite data using sample measurements of pigment concentrations from ships at known points in the image, and then extrapolate to other areas in the image assuming that the atmospheric conditions vary gradually between the calibration points.

32. Because the colour of phytoplankton pigments is variable, estimates of phytoplankton concentration derived from satellite measurements are only accurate to about 30 per cent. Direct measurements from ships are considerably better, with an accuracy of about 5 per cent, but the limited precision from satellites is outweighed by the extent of the coverage. Each image recorded by the Nimbus-7 Coastal Zone Colour Scanner, for example, covers an area of 2 million square kilometers of ocean.

33. Measurements of phytoplankton or pigment concentrations must then be converted into estimates of primary productivity. Models of the relationship between the amount of pigment and primary production, taking into account the effects of other factors such as water temperature and solar radiation, are under development and are steadily improving. The next step is to estimate the proportion of the total production of organic carbon that is removed from the surface waters and is sequestered in the deep sea.

34. Satellite observations have greatly improved our understanding of the processes that control primary productivity in the ocean and the part that marine organisms play in the global carbon cycle. One of the first discoveries was the extent of the spring plankton "bloom" at high latitudes and the fact that a large proportion of the spring phytoplankton sinks rapidly to the bottom. The circulation of the deep waters of the ocean is such that they do not reach the surface and make contact with the atmosphere for thousands of years. The spring phytoplankton bloom is therefore an important sink for atmospheric carbon dioxide, more important than previously thought.

F. Pollution monitoring

35. Pollution of the oceans and coastal areas takes a variety of forms, including oil spills, sewage and waste disposal, chemicals that promote the growth of unwanted algae and water weeds, radioactive and other toxic materials, and warm water that can cause harmful effects on marine life.

36. For monitoring oil spills and supporting clean-up operations, satellites provide information on wind and currents as well as a synoptic view of large spills. Satellite data are also extremely useful for identifying spills occurring outside the normal range of patrol aircraft and for monitoring some long-term effects of spills. While the Landsat and Spot satellites provide an excellent overall view of an oil-spill region, they are limited by daylight, cloud cover and their orbital patterns, so that data may not be available at the time it is needed. Data processing and distribution delays also constrain timely availability of data. Satellite radar systems provide an oil-spill detection capability not limited by cloud cover, as has been demonstrated by ERS-1, but the visibility of oil slicks on radar imagery depends on the wave-suppressing effect of the oil,

which is most effective at wind speeds between 4 to 10 m/s. At lower wind speeds the water may be too calm for there to be a detectable calming effect, while at higher wind speeds turbulence disrupts the slick and overcomes the calming effect. Current satellite systems therefore may provide some useful data on oil spills, but they cannot meet the full requirements for frequent monitoring under all conditions.

37. While oil spills often provide the most spectacular examples of ocean and coastal pollution, the most widespread and serious sources of pollution are domestic and industrial sewage disposal and soil and other matter carried from the shoreline by erosion. Those sources have been increasing due to growing coastal populations coupled with the lack of sewage treatment and erosion control. Pollutant concentration decreases with distance from the source, and the open ocean stays relatively clean, but since the coastal zones play a primary role in supporting the aquatic food chain throughout the oceans, the direct effect of coastal pollution can have long-range indirect effects. An understanding of the global effects of coastal pollution requires further study of the connections between human activities, coastal processes, exchanges between the coastal zones and the open sea, and the biogeochemical processes of the global oceans. While pollutants cannot be chemically identified by satellite remote sensing, polluted waters flowing into the ocean often differ in colour or temperature from the cleaner ocean water, allowing the identification of pollution sources and the study of distribution and mixing patterns.

38. Initial data from the ERS-1 satellite have demonstrated the use of radar to monitor a variety of coastal processes, including erosion and sediment transport along the coast, coastal profile changes, tides, wave convergence and diffraction patterns, relations between wavelength and wave height, and, in a number of cases, coastal discharges.

G. Ice monitoring

39. The polar regions, and in particular the ice caps, are increasingly being recognized as important factors in global climate change, but surveys are difficult due to the vast areas involved, the logistical difficulties and the high costs of polar field work. Polar-orbiting satellites therefore are an ideal tool for regular monitoring of polar conditions. Radar and other microwave sensors are particularly important since they can observe during the long polar night and through clouds.

40. An accurate knowledge of the topography of ice-covered regions is an essential requirement for determining ice sheet dynamics, mass balance variations, and the role of ice sheets in the climate system. Satellite radar altimetry now permits long-term monitoring of the ice sheets and ice shelves and their responses to climate change. The results from the radar altimeters on the United States Geos-3, Seasat and Geosat satellites have demonstrated an accuracy far superior to existing surface and airborne surveys. Those satellites, however, were in orbits that precluded coverage above 72° latitude, leaving half of Greenland and most of Antarctica unmapped.

41. The launch of ERS-1 in 1991 extends satellite altimetry to 82° latitude north and south, allowing the first topographic mapping of the major part of the Antarctic ice sheet, including the Ross and Ronne-Filchner ice shelves and West Antarctica. West Antarctica is of particular interest since the ice rests mainly on bedrock below sea level and may be climatically unstable. The radar altimeter data are also to be used to study the circulation of the Antarctic Circumpolar Current.

42. In the Arctic, analysis of ERS-1 radar altimeter data to study the Earth's gravitational field indicates that existing gravity surveys are drastically wrong in many geodynamically important regions, particularly where relatively young, spreading sea-floor ridges and large gravity anomalies are located. The gradual accumulation of data from different orbital tracks should provide unprecedented high spatial resolution and lead to a major improvement in detailed marine gravity-field modelling.

II. OCEAN OBSERVATION SATELLITES

A. Overview

43. Satellites have been used for observing the Earth since the first meteorological satellites were launched in the 1960s. While meteorological satellites are designed primarily for cloud and atmospheric observations, improvements in the sensors over the year have made them increasingly useful for low-resolution, large-scale ocean and land observations as well. In the 1970s, the first remote sensing satellites designed for detailed study of the land surface were launched and have been collecting high-resolution multispectral scanner data ever since. Beginning in the late 1970s, experimental oceanographic satellites and sensors were launched, but unlike the meteorological and land remote sensing satellites, oceanographic satellites have generally been single satellites with quite limited lifetimes and have therefore not provided a continuing source of ocean observations. With the more recent launchings of the Marine Observation Satellites (MOS-1A and 1B), ERS-1 and JERS-1, satellite oceanography is expected to advance rapidly in the future.

B. Meteorological satellites

44. Meteorological satellites can be divided into two groups, polar-orbiting satellites and geostationary satellites. Polar-orbiting satellites orbit at relatively low altitudes, around 1000 km, and can provide coverage of the entire world, including the polar regions, once or twice a day. The geostationary satellites revolve in synchrony with the Earth's rotation at an altitude of about 36,000 km above the equator, thereby appearing to remain stationary above a fixed point on the equator and providing views of the same area of the Earth as often as every 20 minutes. Since geostationary satellites are, by their nature, above the equator, they cannot view the polar regions above about 70° north and south latitude.

45. The most widely used polar-orbiting meteorological satellites are the NOAA satellites, maintained on an operational basis by the United States National Oceanic and Atmospheric Administration (NOAA). The sensor of primary interest for ocean observations is the Advanced Very-High Resolution Radiometer (AVHRR), which measures reflected visible and infrared light and emitted thermal infrared radiation with a resolution of 1 km.

46. Geostationary meteorological satellites include the United States Geostationary Operational Environmental Satellites (GOES), the Western Europe Meteosat satellites, the Japanese Geostationary Meteorological Satellites (GMS) and the Indian Insat. From their geostationary positions, those satellites provide continuous observations covering one third of the globe from 70° north to 70° south latitude, and five satellites provide full global coverage except for the polar regions. The major data of oceanographic interest from the geostationary satellites are the thermal infrared data with a resolution of 5 to 10 km depending on the satellite.

47. For ocean applications, the most widely used meteorological satellite data are the NOAA AVHRR thermal infrared images of cloud-free ocean areas showing sea-surface temperature. In polar regions, the visible-band images also provide useful information on sea-ice extent and movement. A major advantage of meteorological satellite data is that they can be received by inexpensive ground stations throughout the world without charge or restriction. Over 125 countries are receiving and using meteorological satellite data.

C. United States oceanographic satellites

48. The United States has launched a variety of experimental satellites that have demonstrated oceanographic remote sensing capabilities: Geos-3 (launched in 1975) which first demonstrated radar altimetry for global ocean circulation and wind and wave observations; Seasat (launched in 1978), which carried the first imaging radar for wave and ice studies, a scatterometer for measuring wind speed and direction, and an improved radar altimeter; and the Coastal Zone Colour Scanner (CZCS) on the Nimbus-7 satellite (launched in 1978), with a multispectral scanner designed specifically for mapping ocean colour.

49. The CZCS was a multispectral scanner with six spectral bands, including three narrow bands in the blue and green spectrum where water penetration is greatest. The images had a resolution of 1 km and a higher sensitivity to small differences in reflectance than is required for land observations. Applications of the data included comparing blue and green reflectances, corrected for atmospheric effects, to estimate concentrations of phytoplankton pigment. Only one CZCS was flown, providing data from 1978 to 1986, and no comparable sensor has been flown since. The United States and Japan are planning ocean colour sensors for future missions, including the United States SeaWiFS (Sea-viewing Wide Field-of-view Sensor) with more spectral bands, higher sensitivity and the same 1 km spatial resolution.

50. The United States Geosat satellite was launched in 1985 with a precision radar altimeter. For the initial "Geodetic Mission," the satellite was placed in an orbit with non-repeating ground tracks in order to obtain a detailed global map of mean sea level. For the second mission, the "Exact Repeat Mission," the satellite operated in a 17-day repeat orbit, allowing observation of changes in sea level. Although the primary objective of the Geosat mission was to operate over the oceans, echoes were also collected over ice and land, particularly over Antarctica, where the accuracy in altitude averaged about 40 to 80 cm.

D. Cosmos/Okean

51. Since 1979, the Soviet Union has launched a number of oceanographic satellites as part of its Cosmos series of satellites. The first two experimental satellites were Cosmos 1076, launched in 1979, and Cosmos 1151, launched in 1980. Both satellites carried a multispectral scanner, an infrared radiometer to measure sea-surface temperature, and a relay system to pick-up signals from remote buoys.

52. In 1983, the USSR launched Cosmos 1500 with an imaging radar on board, designed to cover the world's oceans, with special attention to the Arctic, where ice and weather conditions are crucial to shipping. Data from the satellite could be either transmitted in real-time or stored for later transmission to ground centers in Moscow, Novosibirsk or Khabarovsk. The radar images cover a swath 500 km wide with a spatial resolution of about 1.5 km, operating at a wavelength

of 3 cm (X-band). A multispectral scanner provides images with the same 1.5 km resolution, and a multichannel microwave radiometer operating at 0.8 cm, 1.35 cm and 8.5 cm provides surface-temperature data. Subsequent satellites with similar capabilities include Cosmos 1602 (1984), Cosmos 1766 (1986), Cosmos 1869 (1987) and Okean 1 (1988), Okean 2 (1990) and Okean 3 (1991).

53. The Cosmos/Okean radar system has been particularly useful for identifying ice fields and estimating the depths of icebergs and glaciers. In October 1984, Cosmos 1500 radar images obtained at night through thick cloud cover found a path through the ice for ten vessels trapped in Long Strait between the east Siberian and Chukchi seas. In 1985, Mikhail Somov, an arctic explorer who had become trapped near the Russkaya polar station, was guided to safety by satellite radar images.

54. The radar data has been used to distinguish old ice from newly formed ice, locate cracks and crevices, find channels under the ice, and identify oil spills at sea. Data from Cosmos 1500 has been used to compile an ice map of Antarctica, identifying new ice formations and an extinct volcano on Queen Maud Land. At the other end of the climate spectrum, radar images of the Sahara desert showed circular structures in Mauritania that may be the remnants of an ancient fortress now buried in sand.

55. The Cosmos/Okean system has also provided information on storms over the oceans. Multispectral and radar images of the Gulf of Finland have revealed strong west winds that threatened flooding in St. Petersburg. In August and September 1984, the satellite radar tracked hurricane Diana off the east coast of the United States, providing very precise estimates of surface wind velocities of the hurricane while it was still at sea.

E. Japan's Marine Observation Satellites

56. The first Marine Observation Satellite (MOS-1A), launched by Japan in 1987, is still fully operational. Based on the experience with MOS-1A, an improved MOS-1B spacecraft was launched in 1990. The two satellites carry the Multispectral Electronic Self-Scanning Radiometer (MESSR), which provides images in the visible spectral region with a resolution of 50 meters, and the Visible and Thermal Infrared Radiometer (VTIR), which provides images with a resolution of 900 m in the visible and 2.7 km in the thermal infrared. Each satellite provides repeat coverage every 17 days, and the two satellites together double the frequency of coverage. All MOS data are available to the scientific community.

57. As an example of the applications of the data, the expansion of an anoxic area in the Venice lagoon has been mapped, and in the Lagoon of Grado a number of distinct areas of industrial waste could be identified. Analysis of the data has indicated that future satellites should have higher radiometric resolution in order to distinguish more marine features of interest, and that many coastal processes require more frequent coverage for their dynamics to be accurately studied.

58. In 1992, the Japanese Earth Resources Satellite (JERS-1) was launched with both an imaging radar system and a multispectral scanner. Both systems have a resolution of about 20 m. The multispectral scanner has three spectral bands in the visible spectrum and four in the near-infrared. The sensors are designed for both land and ocean applications, including fisheries, coastal monitoring, disaster warning and environmental protection.

F. European Remote Sensing Satellite

59. The European Space Agency, in 1991, launched the European Remote Sensing satellite (ERS-1) carrying instruments operating in the microwave range for all-weather observations of oceans, including ocean topography, sea-surface temperature, sea ice, surface-wind velocity, and wave height and energy. The data are transmitted to the ground and recorded by a network of ESA and national ground stations, where the data are quickly processed to generate "Fast Delivery" products, which are electronically distributed to operational centres via satellite or land-lines within three hours of acquisition. The data is also delivered to the Processing and Archiving Facilities (PAF) established in Germany, Italy and the United Kingdom for long-term archiving and precision processing. The European Space Research Institute (ESRIN) operates the ERS-1 Central Facility (EECF), which assists users in identifying their data needs and schedules satellite operations.

60. The largest sensor on ERS-1, called the Active Microwave Instrument (AMI), consists of two radar systems, an imaging radar that produces images of the sea surface with a resolution of 25 meters, and a scatterometer that measures wind speed and direction with a spatial resolution of about 25 km. The imaging radar looks down from the satellite at an angle of 23° from the vertical and observes a swath 100 km across. The imaging radar is normally used no more than seven minutes per orbit because of its high energy consumption, but observations up to about 12 minutes in duration are possible. One year after launch, an average of 650 scenes per day are being acquired. Some 300,000 images have been received by ground stations, including stations at Kiruna, Sweden, and Tromsø, Norway.

61. The other radar component of the ERS-1 Active Microwave Instrument is the wind scatterometer. Winds moving across water roughen its surface, which reflects, or scatters, radar signals in a pattern that depends on the speed and direction of the wind. The scatterometer observes a swath 500 kilometers wide to one side of the satellite's track. Three antennas are used to look at the swath from different angles: one looks perpendicular to the satellite's track, another looks 45° forward and the third 45° backwards. Each antenna measures the reflected radar signal from a series of 25 km elements across the swath. The three sets of measurements are then processed to determine the wind speed, to an accuracy of 2 m/s, and direction, to an accuracy of 20°, in each cell. The data actually allows two possible wind directions in roughly opposite directions, but meteorologists can normally determine the correct direction by comparing the results of adjacent cells. They can also use other sources of wind data, such as weather ships or weather predictions, to help them determine the true direction of the wind.

62. The second major instrument on ERS-1 is the Radar Altimeter. In addition to providing more accurate measurements than previous satellite altimeters, ERS-1 provides coverage up to 82° north and south latitude, permitting for the first time mapping of the major part of the Antarctic ice sheet. A further important feature of the ERS-1 altimeter is the inclusion of an "ice tracking mode", which permits accurate measurements over surfaces with greater topographic relief than could previously be measured, although with reduced height resolution.

63. A preliminary topographic map of the Antarctic coast has been compiled from ERS-1 altimeter data, with a resolution of about 350 km determined by the initial 3-day orbit-repeat pattern. The resulting topographic map shows excellent agreement with the best available map compiled from ground survey data. This early result indicates the major improvement in Antarctic topographic mapping which will be possible when the planned 35-day and then 176-day orbit-repeat cycles have been completed. The final result will be topographic maps with a resolution of about 6 km.

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64. ERS-1 carried one passive sensor, the Along-Track Scanning Radiometer (ATSR), which comprises an Infrared Radiometer and a Microwave Sounder. The Infrared Radiometer provides measurements of sea-surface temperature to an accuracy of 0.5°C with a resolution of 50 km. Measuring sea-surface temperature is difficult because moisture in the air absorbs some of the infrared radiation returning to the satellite and thus distorts the conversion of radiation to temperature. The radiometer solves this problem by making a number of different measurements and comparing the results. First, radiation is measured in four separate wavelengths in the thermal infrared spectrum. Since atmospheric moisture attenuates radiation of different wavelengths at different rates, comparison of the radiation detected at the four wavelengths can determine and correct for the attenuation. Secondly, the radiometer looks twice at each point in its 500-kilometer-wide swathe. It looks directly downward, and also ahead along the track of the satellite at an angle of 52°. By comparing the radiation received from each point through two different paths, another estimation of the attenuation can be made and corrected for.

65. The Microwave Radiometer measures thermal radiation directly below the satellite using two frequencies particularly sensitive to water vapour in the air. In addition to providing surface temperature data, the measurements are also used to correct for the effect of water vapour on the Radar Altimeter measurements, thereby increasing the accuracy of the latter. All of the thermal data, along with internal calibration readings, are transmitted to the ground once per orbit for processing into maps of sea-surface temperature. However, due to the length of the orbit-repeat cycle and because clouds prevent infrared measurements, it usually takes a few weeks to build up a complete global map of sea-surface temperature.

66. ERS-1 has a design life of three years, limited mainly by the stress on the microwave instruments from continually generating high-powered signals. ESA has approved a second satellite, ERS-2, which is due to be launched in early 1995 and will carry similar instruments plus a new sensor to monitor atmospheric ozone. This should be followed towards the end of the decade by two new remote sensing satellites, Envisat-1 and Metop-1, to be launched by ESA in cooperation with the United States as part of the space station programme, which should put ocean remote sensing on a firm long-term footing.

G. Topex/Poseidon

67. The Topex/Poseidon satellite, launched in September 1992, is dedicated to the study of global ocean circulation and its medium-scale variations. The observations are expected to play a central role in the World Ocean Circulation Experiment (WOCE) of the WCRP, which is to study ocean circulation and its role in climatic processes, including heat transport from equatorial regions to the poles, ocean moderation of atmospheric warming effects, and carbon dioxide exchange between the ocean and atmosphere. The data will also be used in the Tropical Oceans - Global Atmosphere (TOGA) programme, in which a combination of surface and space observations is expected to improve the qualitative understanding of ocean circulation and its influence on climate. In addition, the precise altimeter data will be used to study global tidal patterns and other sea-level variations and the gravity field over the oceans. The simultaneous operation of the ERS-1 and Topex/Poseidon altimeters provides an opportunity for cross-calibration to improve accuracy.

68. The Topex/Poseidon mission is a cooperative effort between France and the United States, with the United States providing the spacecraft platform, France providing the launch on an Ariane rocket, and both countries providing sensors. The United States provided the dual-frequency radar altimeter and the three-channel microwave radiometer, while France provided the experimental single-frequency radar altimeter. The altimeters should provide global ocean topography data with a precision better than 10 cm. To allow precision orbital tracking, the satellite will carry several high-precision localization systems, including laser reflectors and a Global Positioning System (GPS) receiver provided by the United States and the Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) system provided by France.

69. The primary instrument is the dual-channel altimeter, which uses proven technology and is designed to determine satellite altitude with a precision of 2 to 3 cm. The use of two frequencies, 13.6 GHz and 5.3 Ghz, allows correction for distorting effects caused by ionospheric electrons. The time for the reflected signal to return to the satellite gives the distance between the satellite and the surface, and the shape of the reflected signal will be used to determine wave height and surface wind speed. For circulation studies, the differences between the observed topography and that expected from the gravity field will be used to calculate the direction and speed of the current. Thirty-eight teams of scientists of nine different nationalities are evaluating the data, which will later be available to the world scientific community as a whole.

70. The satellite also carries the experimental Poseidon altimeter operating at a single frequency of 13.6 Ghz, incorporating recent solid-state technology that reduces its mass, volume and power consumption by a factor of four with respect to existing technology. In addition, the transmitted data rate is reduced by a factor of seven through on-board processing. The data will be corrected for ionospheric effects on the basis of the dual-frequency DORIS system.

71. The three-channel microwave radiometer, operating at frequencies of 18 GHz, 21 GHz and 37 GHz, measures the amount of water vapour in the atmosphere and allows correction for altimetric errors due to humidity in the lower atmosphere.

72. Precise determination of the satellite orbit in order to convert altimetric data into sea-level data is the most difficult aspect of the mission, requiring an accuracy of 10 cm or less between the satellite and the ground reference level. Three independent tracking systems are used to precisely determine the orbit. One system is a ring of laser corner-reflectors located around the altimeter antenna, which enable the satellite to be tracked with an accuracy of a few centimeters by a network of twelve ground-based laser tracking stations around the world. The DORIS system determines satellite velocity by on-board measurement of the Doppler shifts of two precise microwave signals transmitted by a global network of about 50 ground beacons whose positions are known within a few centimeters. The third system, the GPS receiver, uses a new technique of differential ranging from GPS satellites and is expected to be accurate to 10 cm.

H. Radarsat

73. Radarsat, being developed in Canada for a 1995 launch, will carry as its main sensor an imaging radar operating at a frequency of 5.3 GHz and designed to provide data for both land and marine applications. The radar swath to the side of the satellite track can be electronically altered in width and spatial resolution to suit particular applications. The standard mode will have a swath-width of 100 km and a resolution of 25 m, while other modes will range from a

45 km swath with 10 m resolution to a 500 km swath with 100 m resolution. The 500 km swath will provide the unique opportunity to cover the entire Arctic, from 75° latitude to the North Pole, every day, and complete coverage of the globe above 50°N every three days.

74. The higher-resolution swaths can be steered either closer to the subsatellite track, for such applications as ice classification or oceanographic studies, or further away from the subsatellite track, where the higher incidence angle up to 50° provides relief information for studying geological structure and detecting icebergs. Processed and interpreted information should be available within a few hours of acquisition for applications requiring timely data, such as navigation in ice-covered waters or disaster assessments.

75. Radarsat will have enough power to operate the radar for a maximum of 28 minutes during each 101-minute orbit. Outside the range of ground stations, the satellite will have the capability to record and store 10 minutes of data per orbit for later transmission to the ground. A total of over 5 million square kilometers can be covered during each orbit. Radarsat will be launched by the United States on a Delta rocket into a sun-synchronous orbit inclined 99° to the equator at an altitude of about 800 km and with an orbit repeat-cycle of 24 days.

III. ECONOMIC APPLICATIONS OF SATELLITE OCEANOGRAPHY

A. Fisheries

76. Applications of meteorological satellite data for planning fishing operations began in 1971 in the United States in an effort to assist purse-seine tuna fishing boats in California. Today, information relating to fish location is provided to fishermen by government agencies in France, Japan, New Zealand, the Russian federation, the United States and other countries. Both geostationary and polar-orbiting meteorological satellites are used to identify major upwelling areas through the analysis of sea-surface temperature patterns on infrared images. In the United States, this information has been used extensively by the tuna, salmon and swordfish fisheries. An evaluation of a 1975 experiment estimated that the tuna and salmon industries were able to save $580,000 in fuel that year through faster location of fish concentrations.

77. Areas of upwelling and high productivity have also been identified using visible and near-infrared data from the Coastal Zone Colour Scanner (CZCS) on the Nimbus 7 satellite. The water colour data were used to map global and regional plankton concentrations and movements and to estimate primary productivity. In the Pacific Ocean, a clearly defined line of colour was observed along the equator indicating where deep water rich in nutrients rises to replace water that is flowing towards the poles. That upwelling stimulates the growth of phytoplankton and supports fisheries. Those satellite observations have provided a new understanding of how extensive the productive waters along the equator are and how important the equatorial ocean is in the global carbon cycle.

78. A major international programme to study marine productivity is the Joint Global Ocean Flux Study (JGOFS), which will study the fluxes of carbon and other biological elements in the global ocean and the exchanges of these elements between the atmosphere, the sea surface and the deep sea. While detailed quantitative chemical analysis will be done from the surface, space observations, particularly of phytoplankton, will be used to extend local studies to the global scale.

79. In Sweden, Landsat Thematic Mapper (TM) data is being used for monitoring algae blooms along the coasts. Comparison of spectral bands provides an estimate of the amount of chlorophyll in the surface waters, which can be converted to algae concentration. The blooming of diatomaceous algae in the spring normally gives rise to chlorophyll concentrations of about 20 to 30 microgrammes per liter, which can be readily measured on Landsat TM data with its sensitivity of 5 to 10 microgrammes per liter.

80. Sea-ice forecasts are also important to fishermen since ice can limit access to fishing areas and damage vessels and fishing gear. In 1980, for example, United States king crab fishermen lost more than $3 million worth of crab pots to sea ice. Those fishermen now rely on ice charts of their area to reduce losses. Canada, Norway and the United States are among the nations that routinely provide satellite-derived ice advisories to fishermen.

B. Shipping operations

81. During the past decade, the marine transportation industry has become dependent on satellite-derived information for planning ocean transport. Ship routing services provide advisory messages to vessels prior to departure via telex or fax and continue to update the information every few days during the voyage via maritime satellite communications or marine radio. Those services can reduce the transit time of vessels, thus reducing fuel consumption and operational expenses and providing faster delivery for customers. Ship routing services were pioneered by the 1975 United States Gulf Stream experiment using satellite-derived sea-surface temperatures. A recent study of 25 voyages made between the West Coast of the Unites States and Japan indicated that satellite-derived information could produce an average saving of 20 hours per voyage.

82. The Norwegian Coast Guard, which is responsible for monitoring Norway's Exclusive Economic Zone, currently uses aircraft, large vessels with helicopters and smaller vessels to keep track of as many as a thousand vessels at a time engaged in fishing, other commercial activities or just passing through. The monitoring functions include ship detection, location, classification and identification. Experiments using Seasat and ERS-1 data have indicated that satellite radar images can effectively detect ships, fix their positions and determine size, direction and speed. In the northernmost area, where the satellite orbits are close together, ERS-1 alone can provide the necessary coverage, but further south, more than one satellite would be required for coverage with the necessary frequency.

83. In far northern and southern latitudes, there is a heavy reliance on ship-routing services to find navigable paths through sea ice. Satellite images provide a very cost-effective means for routine monitoring of large areas. The movement of ships themselves can also be monitored on high-resolution imagery by means of their tracks in the ice. Multispectral scanner images from meteorological or remote sensing satellites are useful for ice mapping in cloud free areas, while satellite radar images provide all-weather observations. In addition to distinguishing ice-covered from clear water, radar can distinguish between new ice, which is relatively fragile and easy to get through, and multi-year ice, which is much harder to break through.

84. In the nearly 90 years since a Norwegian navigator first made the trip from Greenland to Alaska, only 53 ships have sailed the Northwest Passage through the islands of northern Canada. Ships that do try usually use helicopters to chart the clearest route and rely on ice-breaker ships

to clear a path. But an experiment conducted from 18 August to 9 September 1992 showed that commercial ships could use the Northwest Passage more or less routinely in the summer months if they had access to ice information from satellite radar. In the experiment, the Japanese passenger ship Frontier Spirit traveled from the western coast of Greenland to Nome, Alaska, in three weeks. The ship's navigators managed to avoid some of the more ice-jammed areas by using images from the ERS-1 satellite transmitted via an Inmarsat communications satellite to the Frontier Spirit. The ERS-1 data were received and processed by a ground receiving station in Fairbanks, Alaska, and converted into images. The images were analyzed by an Alaskan ice expert who produced a map showing the areas with the thickest, most impenetrable ice, and the maps were sent to the ship via normal fax machine within six to twelve hours of acquisition. The images were usable until the ice shifted noticeably, usually about two to four days.

85. A similar experiment was performed in August 1991 to navigate an inhospitable stretch of Arctic waters along the northern coast of Russia - the Northeast Passage. In that experiment, the French ship Astrolabe used ERS-1 images of the ice to find the most efficient, least ice-clogged route from Europe to Japan. The ship completed the voyage in a month, compared with about 40 days required for a trip via the Suez Canal. It has been suggested that with routine ice information, the Northeast Passage might be navigable for as much as six to eight months per year, instead of just a few months in summer.

86. In an Antarctic experiment in July 1992, a German ground station on the Antarctic Peninsula was used to provide satellite radar images and interpreted ice information to the German research ship Polarstern, facilitating its operations in the ice-covered Weddell Sea.

87. Currently, there are a variety of ice monitoring services used by shipping lines. For example, the United States Line, which operates approximately 40 ships around the globe, relies on the NOAA Wefax Notice to Mariners, commercial services, and Canadian government ice reports derived from an analysis of weather satellite and aircraft observations. A recent United Kingdom study reported that ships utilizing ship routing services are saving more than $3000 per day per vessel. Optimum routing has also been shown to reduce not only transit time, but also vessel and cargo damage and insurance premiums.

88. The Norwegian government has established a unit for ocean monitoring, which provides daily ice maps based on microwave radiometer data from meteorological satellites and radar imagery from ERS-1. The demand for current information on ice conditions in the area is expected to grow during the 1990s due to increases in commercial activities, tourism, rescue services, and perhaps to the opening the Northeast Passage to Japan and East Asia for ordinary shipping.

89. The United States Joint Ice Center (JIC) provides shipping with ice information based upon ERS-1 radar data acquired and processed at the ground station in Fairbanks, Alaska. The satellite data are transmitted from the ground station through satellite links to JIC, where they are analyzed together with auxiliary information to generate ice-type and coverage maps, which are then distributed to ships by fax.

90. Finland relies on ice-breakers to keep ports open throughout the winter months and uses satellite observations to deploy the ice-breakers efficiently and minimize costs. To provide daily ice information, imagery from meteorological satellites is computer processed to improve its quality and to make interpretation easier and is then sent via radio to the ice-breakers. The

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results have been good, but meteorological satellite ice observations are limited by cloud cover. As part of International Space Year (ISY), a Real-Time Ice Monitoring Demonstration (RTIMD) project using ERS-1 data was carried out to examine how satellite radar data could be integrated into operational ice monitoring. Later in the 1990s, when additional radar satellites are in orbit, it is expected that radar data will be the basis for daily ice reports.

C. Offshore oil and gas production

91. Offshore oil and gas wells are often drilled in hostile ocean environments that require information on ocean and ice conditions. In such areas as the Beaufort Sea, for example, floating ice islands can intrude into drilling platform areas and, if not predicted and avoided, cause loss of life and equipment. The Canada Centre for Remote Sensing (CCRS) has provided regular ice reports based upon meteorological satellite and aircraft data. The Centre estimates that over $5 million per year is saved through the use of satellite observations for planning more detailed aircraft ice-reconnaissance flights. In 1975, during the construction of the Trans-Alaska oil pipeline and the development of the Alaskan North Slope oil field under unusually cold summer conditions, satellite observations of sea ice allowed equipment barges to reach Prudhoe bay and prevented a one-year delay in construction.

92. Satellite observations can also be used for identifying and studying sensitive environmental areas prior to exploration. For example, areas of high biological productivity associated with upwellings or currents can be identified as areas to be protected.

93. Severe weather always presents a major threat to offshore operations, so accurate storm warnings are essential. In Norway, polar low-pressure areas that produce strong winds at northern latitudes are being forecast for the oil industry through the analysis of meteorological satellite data. Those forecasts can reduce greatly the loss of both equipment and personnel. Mapping and forecasting ocean currents and eddies are also important to the safety of oil-exploration and production equipment. Sea-surface temperature maps derived from meteorological satellite data reveals current patterns and can be used to predict eddies that spin off of major currents.

94. Extreme sea states are also of great concern to the operators of off-shore drill rigs. Satellite radar, scatterometer and altimeter data provide information on surface wind velocity, wave height, wavelength and wave direction. That information can then be used, together with theoretical models, to generate sea-state forecasts.

D. Oil spill monitoring

95. Several satellite systems have been used with variable success for detecting oil in the marine environment as a result of major oil spills. In 1989, the Exxon Valdez grounded on Bligh Reef, Alaska, releasing 10,000,000 gallons of oil into the waters of Alaska's Prince William Sound. This spill was detected using the thermal infrared band of the NOAA AVHRR sensor at night, although low-altitude aircraft flights and ship observations were required to confirm the detection and map the spill. Similar procedures were used during the Mega Borg spill in 1990 in the Gulf of Mexico, which released 3,900,000 gallons of crude oil.

96. In January 1991, during the Gulf War, reports spread of the world's largest oil spill, estimated at 10 million barrels released as an environmental military weapon from oil terminals in Kuwait. Multispectral imagery from Landsat 4 detected an oil slick close to the Saudi coast about 100 miles south of the Kuwait terminals in early February. Later, analysis of a satellite image acquired in mid-February prompted officials to substantially reduce the estimate of the spill. The Landsat Thematic Mapper, which can detect the high reflectivity of oil in the mid-infrared spectrum, was found particularly useful for mapping oil slicks. The large-area overview provided by the satellites were complemented by detailed aircraft observations.

E. Disaster warning

97. Since the introduction of operational meteorological satellites, no major hurricane or tropical cyclone has escaped detection, regardless of its location on the globe. Using computer analysis of satellite data, meteorologists can estimate the central pressure and the maximum sustained winds of a tropical storm.

98. Warnings of ocean storms, high waves and high tides in Southeast Asia and the Pacific region are especially critical due to the high population densities found in low-elevation coastal areas. To meet these needs, most countries in the region rely on the direct reception of data from NOAA polar-orbiting satellites or the Japanese GMS or Indian Insat geostationary meteorological satellites. Warnings based on observations by those satellites are used to evacuate people from low-lying areas threatened with inundation.

99. In the United States, satellite tracking of storms has resulted in savings of over $1.8 million per year as a result of more efficient use of aircraft weather reconnaissance operations, but the full economic value of advance hurricane warnings has not yet been determined. A review of the number of fatalities during the 25 years prior to satellite-based warnings reveals a total of 2163 deaths in the United States. During the initial 25 years of satellite observations, there were only 800 hurricane-related deaths, but how much of this reduction was due to improved forecasting is unknown.

IV. FUTURE PROSPECTS

100. The applications of satellites for ocean resources development depends on international cooperation. While remote sensing satellites like Landsat and Spot and meteorological satellites provide some useful oceanographic satellite information, satellite systems designed specifically for oceanography have tended to be experimental and therefore have not provided continuous or consistent data. The experimental character of most satellite oceanography makes exchange of information and experience particularly important for developing practical applications.

101. The launching in recent years of MOS, ERS-1, JERS-1 and Topex/Poseidon and plans for the launching of other oceanographic satellite systems in the next few years, promise to make satellite oceanographic data more routinely available. The resulting increase in the volume, variety and continuity of satellite data should stimulate increased operational use of satellite oceanographic data as well as the developments of new applications.

102. The increased availability of data from satellite radar systems and other microwave sensors, with their all-weather capability and their unique capabilities for observing sea-surface conditions and ice characteristics, marks a major change in the practical and operational applications of satellites for maritime development.

103. While satellite systems designed specifically for ocean observations are essential for ocean applications, studies of ocean processes usually involve a variety of data sources, including meteorological satellites for frequent large-area monitoring, remote sensing satellites for medium-scale observations and coastal zone monitoring, and aircraft, ship, buoy and shore measurements for detailed study of particular areas. The need for data from different sources means that international and regional cooperation and coordination will be required to realize the potential benefits of satellite data for ocean applications.

104. The practical applications of satellite data are often based on theoretical understanding of ocean processes that are in turn based on the analysis of large quantities of data collected in many areas under many conditions. Many of the natural phenomena the oceanographic satellites are designed to observe, including coastal processes and climate change, evolve over months and years, so consistent data for long periods are essential to the scientific understanding of the oceans and their long-term effect on human activities and the environment. It is already clear that the interactions between ocean processes, the weather and growing and living conditions on land are extensive and complex, and ocean research will produce long-term benefits, not just for maritime activities, but in many other areas of human life as well.

105. The increasing power and decreasing cost of microcomputer systems has made possible computer processing and analysis of satellite data at the local level. Image processing programs and geographic information systems are available for applications of Landsat, Spot, AVHRR, CZCS and other satellite data. In general, it is most convenient and cost-effective for users to obtain data that has been calibrated and corrected for systematic radiometric and geometric distortions at larger central processing facilities and to perform only the analysis specific to their applications. While data can be obtained from the satellite operators, routine and rapid access to data usually requires a regional or national receiving and processing facility.

106. Due to the experimental character of most oceanographic satellites in the past, few education and training programmes exist to train users of those satellites. The establishment of such programmes will be essential to the development of the operational use of satellite oceanographic systems.

107. Oceanographic satellite systems have an important role to play in efforts to protect the global environment. Those efforts, to be successful, must involve active participation by all countries, and the global coverage and broad perspective of satellites provide a unique opportunity for involving all countries in environmental monitoring. Special efforts will be required to ensure that scientists, managers and planners from developing countries have access to the data, to information on the latest technical developments, and to opportunities for education and training in the field.

108. More studies are needed on the economic benefits of satellite applications for ocean resources and operations. Such studies will encourage investments in satellite and applications systems and will provide guidance to countries in planning programmes of satellite oceanography. In the current international economic atmosphere, it is particularly important that

people involved in research and development activities be able to provide economic justification for their important work.

109. In all aspects of satellite oceanography, international cooperation is essential to the development of the field and to enabling all countries to benefit from the technology. While some forms of cooperation can best be undertaken by international organizations at the global level, other forms can be most effectively organized at the multilateral, regional or bilateral level. While formal intergovernmental agreements may be necessary for some large projects, cooperation through non-governmental professional associations and informal cooperation between individual scientists, managers and planners are also essential for the full benefits of satellite oceanography to be realized.

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